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The Skill Premium, Technological Change and Appropriability*

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Abstract

In the US the skill premium and the non-production/production wage differential increased strongly from the late 1970s onwards. Skill-biased technological change is now generally seen as the dominant explanation, which calls for theories to explain the bias. This paper shows that the increased supply of skill - which is usually seen as countervailing the rise in skill premiums - can actually *cause* rising skill premiums. The analysis starts from an R&D-driven endogenous growth model. Our key assumption is that skilled labour is employed in non-production activities that both generate and use knowledge inputs. If firms can sufficiently appropriate the intertemporal returns from these activities, skill premiums may rise with the supply of skilled labour. The degree of appropriability is endogenous and rises with the supply of skills. As a result, the skill premium first falls and then increases when skilled labour supply rises. Simultaneously, patents per dollar spent on R&D fall.

Keywords: wage inequality, growth, technological change, appropriability

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1. Introduction

Wage inequality decreased in the 1970s and has increased since the early 1980s in the US (see Table 1). The increase in inequality in the 1980s has drawn a lot of attention. Four explanations have been proposed: a change in educational attainment,[1] a change in institutions like minimum wage laws, a change in the bias in technological change and increased trade with low-wage countries. Through a process of elimination of explanations that are not clearly supported by the data, biased technological change is argued to be the dominant explanation for the observed pattern in wage inequality. To explain wage inequality further, given this state of affairs, there are two way to proceed. The first is to test empirically the claim that a bias in technological change is responsible for the increase in inequality. Krueger (1993) examines whether there exists a technology-related skill premium. Computer-use turns out to be related directly with a skill premium.[2] A second route to strengthen the case for a biased-technological-change explanation, which is the default explanation , is to explain how a biased technology shock arises and how it is translated into inequality. Most literature, taking the second route, explains how the bias relates to inequality (for example Greenwood and Yorukoglu, 1997).

This paper extends these contributions by taking the next step of explaining where the bias in technology comes from. We develop a model that predicts that an increase in the supply of educated workers *causes* a bias in technological change which can cause the relative wage of skilled workers to increase. In particular, we argue that the *steady increase* in the supply of educated workers that most Western economies have experienced in the postwar period can be seen as the driving force behind the *non-monotonic* time pattern of skill premiums. Since both the pace and the nature of technological change are endogenous in our model, we are able to establish a connection between observed trends in wage inequality and technology indicators. Wage inequality is inherently linked to R&D productivity; the same shock that drives wage patterns also explains the decline in patents per dollar spent on R&D.

[1] Educational attainment clearly increased (see Table 1), as such this implies a downward pressure on the relative wage of skilled workers. An alternative way of interpreting the evidence, however, is that the quality of high schools decreased (and hence the quality of unskilled workers decreased). This might put downward pressure on the relative wage of unskilled workers.

[2] This is not uncontroversial. DiNardo and Pischke (1997) argue that the relation is spurious. However, Autor, Katz and Krueger (1998) reconfirm earlier findings of Krueger (1993).

Our key assumption is that skilled workers perform tasks that are fundamentally different from those of unskilled workers. While unskilled workers contribute directly to (current) production, skilled workers are employed as non-production workers. The latter contribute to the continuous process of organizational change and improvements within a firm that affects the future productivity of the firm. In this process they build on and further expand the knowledge stock that is already accumulated within the firm. Non-production workers both use and produce new knowledge. In this setup, an increase in the supply of skilled workers gives rise to two effects. There is a direct conventional effect that decreases wages of skilled workers in order to induce firms to absorb the increased supply and expand non-production jobs. However, if firms employ more skilled non-production workers, the demand for knowledge inputs in non-production rises. To generate these inputs, skilled workers themselves should be employed, so demand for skilled labour increases. This second effect counteracts the conventional effect. This is an induced *investment* effect: the expansion of non-production jobs triggers investment in organisational knowledge capital. If sufficiently large, the investment effect may offset the conventional effect. Investment incentives are significant if the cost of capital does not increase too quickly in response to increased investment and if the returns to investment can be sufficiently appropriated. We find that under these circumstances, the firm is willing to attract skilled labour at a higher wage if educational attainment raises, that is, the demand curve for skilled labour slopes upward.

The degree of appropriability as the key determinant of the skill premium pattern is endogenous in the full version of our model. In particular, we distinguish between two types of knowledge investment: first, firms can accumulate knowledge internally (inhouse R&D), and, second, they can buy technology in the patent market. Internal knowledge accumulation allows firms to internalize part of the intertemporal knowledge spillovers from research, but this is impossible when taking out patents. We show that at low levels of the supply of skilled labour, patents are the dominant source of technology acquisition, appropriability is weak, and skill premiums are mainly determined by the conventional mechanism. However, with a high supply of skilled labour, most research effort is endogenously allocated to firm-specific knowledge accumulation, appropriability has improved, and the induced investment effect dominates the conventional effect. Hence, if skilled labour becomes gradually more abundant, the share of patents in total R&D output declines steadily, while the skill premium first decreases and then increases.

Table 1 Non-production wage-bill and employment share, relative wage and R&D intensity and productivity in the US 1973-1989.[a]

	1973	1977	1981	1989
Non-production wage-bill share	.337	.351	.397	.414
Non-production employment share	.246	.261	.285	.303
Non-production/production wage differential	1.55	1.53	1.53	1.62
Supply of high education[bc]	10.8		16.6	21.5
R&D intensity manufacturing	.063	.062	.077	0.1
Patents per million $ R&D[d]	1.7	1.5	1.1	1

[a] Source: Machin and Van Reenen (1998).
[b] Source: OECD Employment Outlook (1993).
[c] Share of college educated, for 1970, 1980 and 1990.
[d] Source: Kortum (1993).

Our model replicates the main stylized facts that guide the wage-inequality debate. First, the majority of US industries have, despite the increases in the relative cost of skilled workers, increased the ratio of skilled to unskilled labour (Bound and Johnson, 1992, Berman, Bound and Griliches, 1994, Katz and Murphy, 1992). Table 1 shows that the wage-bill share of non-production workers increased from the early 1970s to the late 1980s. The non-production employment share increased in both the 1970s as the 1980s whereas the non-production / production wage ratio fell in the 1970s and increased in the 1980s. As a second stylized fact, it is worth stressing that within industry increases in the ratio of skilled to unskilled workers overwhelm the between industry shifts (Bound and Johnson, 1992, Berman, Bound and Griliches, 1994, Katz and Murphy, 1992). Although intersectoral reallocations can be included in our model, we do not want to focus on this aspect. Third, our model replicates the finding that skill upgrading is positively correlated with R&D intensity changes (Machin and Van Reenen, 1988). Finally, our model is consistent with the long-term fall in the number of patents generated per R&D dollar.[3]

This paper relates to the literature that analyses the interaction between technology,

[3] Though not apparent from Table 1, in the late 1980s the number of patents per R&D dollar increased again. We do not focus on this aspect here as it is still unclear how important the numerous institutional changes with respect to the patent system are in explaining this (see Kortum and Lerner, 1998 and Jaffe, 1999).

wage inequality and the endowment of skills. There are two strands. The first takes a biased technology shock as given and explains the effect on wage inequality. Caselli (1999) for example shows how a technology revolution affects inequality if the workforce is heterogenous in training cost. Greenwood and Yorukoglu (1997) analyse how an acceleration in investment-specific technology affects productivity growth and wage inequality if skilled workers have a comparative advantage in technology implementation. These analyses leave unexplained where the technology shock comes from.

The second strand of analysis, including Acemoglu (1998), Kiley (1999), Galor and Tsiddon (1997), Galor and Moav (1998), and Lloyd-Ellis (1999), explains as this paper does where the bias comes from.

Acemoglu s (1998) model and ours have in common that an increase in the endowment of skills induces investment in technology which raises inequality.[4] However, our approach completely differs with respect to the type of investment considered and the associated investment incentives. First, Acemoglu treats skilled and unskilled workers as symmetric factors of production. Investment consists of purchases of research lab equipment. We explicitly acknowledge the different nature of production versus non-production work, where non-production work has an investment character. Second, the investment incentive in Acemoglu s model depends on the market size for innovations targeted at either skilled or unskilled labour. If these markets are not segmented, technological change would not be biased. Our model avoids this extreme degree of market segmentation. Our crucial investment incentive is not market size but the degree to which the value of innovations can be appropriated by firms. Third, induced investment endogenously affects the nature and productivity of research in our model, which allows us to look beyond the labour market effects on which Acemoglu focuses. Our model provides a new testable prediction, born by the data, that the number of patents per R&D dollar decrease by increases in the supply of skilled labour. Fourth, Acemoglu introduces a sector bias where we introduce a bias within sectors which corresponds more closely to the stylized facts mentioned above. Finally, opposite to Acemoglu s results, we find that with decreasing returns in the knowledge accumulation process changes in wage inequality are temporary only.

Galor and Tsiddon (1997) explain the cyclical pattern of wage inequality by the evolution of the return to ability. Workers differ with respect to ability and the returns to

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[4] A similar induced-innovation mechanism is found in Kiley's (1999) deterministic version of Acemoglu's analysis.

ability change because of two types of technological change. First, infrequently occurring major technological breakthroughs raise the return to ability and increase wage inequality. Income distribution shifts only gradually because mobility of workers is not instantaneous. Second, subsequent incremental innovations gradually make technological advances more accessible for low ability workers, which tends to decrease wage inequality.

Galor and Moav (1998) use the assumption of heterogenous ability levels to explain the observed patterns in within-group inequality. Skilled workers have on average higher ability, which allows them to adjust more quickly to new technologies than unskilled workers. An acceleration in technological progress benefits skilled workers and in particular high-ability skilled workers so that inequality both between and within groups rises. We could incorporate this key insight in our model by allowing ability to differ within groups and by allowing the return to ability to rise with technological progress for both production and non-production workers. Our model would then replicate the observed increase in within-group inequality in both the 1970s and 1980s. However, we choose to abstract from this and focus on the mechanism driving *between*-group inequality.

Lloyd-Ellis (1999) explicitly separates out the development of new technologies and the absorption of these in production. For both activities skills are important. Depending on the available distribution of skills, technologies can be introduced faster than they are absorbed such that wage inequality is driven up.

The emphasis in this paper on the investment character of skilled work relates the paper to the literature showing that skilled labour has a comparative advantage in implementing technology and R&D (Bartel and Lichtenberg, 1987).

Finally, this paper uses building blocks from the literature on endogenous growth like, for example, the intentional accumulation of knowledge by profit-maximising firms. We combine the benchmark R&D growth models, where patents are assumed to take care of rent appropriation (e.g. Grossman and Helpman, 1991, and Romer, 1990), with an approach based on firm-specific knowledge. Thus, we assume that firms rely on both in-house R&D and firm-specific knowledge as well as patents developed using the pool of public knowledge (cf. Peretto, 1998 and 1999, Smulders and Van de Klundert, 1995 and Thompson and Waldo, 1994). We use the fact that spillovers are not complete and instantaneous; this fact is well documented (see Jaffe, Trajtenberg, Henderson, 1993). We extend the theory of growth based on firm-specific knowledge by broadening the concept of technological change to organisation change (management etc).

The plan of the paper is as follows. Section 2 introduces the model. Section 3 separates out the role for firm-specific R&D and spells out the relation between this type of investment and the skill premium. Section 4 explores the full model by allowing both for growth based on patents along growth based on firm-specific knowledge. There we endogenise the degree of appropriability. Section 5 concludes.

2. A general-equilibrium model of non-production jobs

2.1 Overview of the model

There is a continuum of firms, each supplying a unique product variant under monopolistic competition. For notational convenience we normalize the mass of firms to unity. Firms hire two types of labour, labelled skilled (H) and unskilled (L). The supply of both types of labour is exogenously given.

As explained in the introduction, we interpret skilled workers as non-production workers to be contrasted to production workers which are supposed to be less skilled (note that the empirical literature that documents the change in the skill premium applies the production/non-production classification). Indeed, education and training results in two types of skills. The more elementary skills consist of basic insights and capabilities to undertake given activities at a certain accuracy. Beyond this type of skills, there are more sophisticated skills to analyse existing activities and to generate new knowledge. Those who obtained the first type of education are called unskilled workers. Those who also obtained the second type are called skilled workers. We may think of skilled workers as marketing managers, organisation experts, financial planners, research lab workers etc.

Firms maximize profits and consumers maximize utility. Consumers have Dixit-Stiglitz preferences over a variety of goods. We consider a closed economy without uncertainty and perfect foresight in which all markets clear.

2.2 Preferences and households' behaviour

The consumer side of the model follows the by now standard approach of growth theory. The representative consumer cares about an index (C) of differentiated consumption goods (x_i) a la Dixit and Stiglitz (1977):

$$C = \left(\int_0^1 x_i^{\frac{\varepsilon}{\varepsilon-1}} di \right)^{\frac{\varepsilon-1}{\varepsilon}} \quad , \tag{1}$$

where ε is the constant elasticity of substitution. Consumers maximize intertemporal welfare that features a constant discount rate (ϑ) and constant elasticity of intertemporal substitution (1/ρ):

$$U_t = \int_t^{\infty} e^{-\vartheta t} \frac{C_t^{1-\rho} - 1}{(1-\rho)} dt \ . \tag{2}$$

Maximization of (1)-(2) subject to the appropriate budget constraints implies that the price elasticity of demand for any good x_i equals ε, and that the change of consumption over time is governed by the Keynes-Ramsey rule:

$$r - \hat{p}_c \ = \ \vartheta \ + \ \rho \hat{C} \ , \tag{3}$$

where r is the nominal interest rate and p_c is the price index for the differentiated consumption good.

2.3 Technology

Each firm produces according to the following production function:

$$x_i \ = \ (f_i^{\beta} n_i^{1-\beta}) \cdot L_i^{\delta} \ \equiv \ F(f_i, n_i, L_i) \ . \tag{4}$$

Final output is denoted x. L are unskilled workers[5] whose effectiveness or productivity depend on a composite knowledge stock or aggregate (organisational) quality index $f_i^{\beta} n_i^{1-\beta}$. Two types of knowledge matter: firm-specific knowledge (f) developed by skilled workers inhouse, and knowledge *(n)* acquired by buying patents from skilled workers active in specialized research firms.

Skilled workers hired inhouse by the firm (H_{fi}) gradually improve the organisation,

[5]Note that we allow for decreasing returns to unskilled labour $0<\delta<1$. The underlying assumption is that the firm also employs a fixed factor whose size is normalized to one.

production technology or (perceived) product quality (through marketing). The one-dimensional variable f captures all these different aspects. The stylized representation of the accumulation process for ideas is as follows:

$$\dot{f}_i = \xi \cdot (f_i^{\alpha} \bar{f}^{\gamma} \bar{n}^{\nu}) \cdot H_{fi}^{\lambda} \equiv G(f_i, \bar{f}, \bar{n}, H_{fi}), \qquad \alpha,\gamma,\nu \in [0,1),\ \lambda \in (0,1] \ . \tag{5}$$

The (non-production) work of skilled workers improves the production environment for the unskilled workers.[6] The term in parentheses captures the different types of knowledge inputs skilled workers use. First, they analyse, exploit and expand the stock of accumulated firm-specific experience and organisational knowledge capital (f_i).[7] Second, skilled workers benefit from knowledge developed for other firms, as captured by the average levels of firm-specific knowledge ($\bar{f}$) and patented knowledge ($\bar{n}$) held by other firms. This second type of knowledge inputs is beyond control of the individual firm and gives rise to the intertemporal knowledge-spillover externality that is familiar from R&D-based endogenous growth models. Firms do not internalise the intertemporal spillovers to other firms because they cannot appropriate the associated returns. However, firms do internalize the intertemporal spillover effect from own knowledge generation to their own non-production activities: they take into account that accumulation of specific knowledge not only affects production but also provides inputs for future research. Since the productivity of own knowledge for future research is governed by elasticity α, this parameter quantifies the role of intertemporal appropriability effects.

Patents are produced in an R&D sector where specicialized research firms may enter freely. Skilled workers hired by research firms (H_n) produce $\chi \bar{n}^{\mu} \bar{f}^{\phi}$ patents per unit of time. The productivity of research firms is increasing in both types of knowledge distinguished. The production function a research firm thus faces is:

$$\dot{n} = \chi \cdot \left(\bar{n}^{\mu} \bar{f}^{\phi}\right) \cdot H_n \ . \tag{6}$$

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[6] There are decreasing returns with respect to skilled labour inputs. This captures the "stepping on toes effect", indicating congestion and duplication in research (see Jones, 1995, for an extensive discussion).

[7] For an extensive discussion on the firm-specific nature of knowledge, see Smulders and Van de Klundert (1995) and Peretto (1999). For an explicit treatment of the tacitness of knowledge, see Dosi (1988).

The knowledge output is sold in a patent market. Appropriability in this research activity is smaller than for firm-specific research. In particular, we assume that a new patent improves production of firms, for which the inventor is fully rewarded, but it also improves productivity of research for which the inventor is not rewarded. Trade in ideas among firms requires a patent register in which technical details and general principles are documented and by which they become freely available to other researchers. As in almost all R&D-based growth models (Romer, 1990, Grossman and Helpman, 1991, Aghion and Howitt, 1998), in our patent sector, researchers build on the total stock of public knowledge, but cannot internalize the contribution they make to this stock.

The importance of our distinction between firm-specific and patentable knowledge, which have different weights in the firm s activities, is supported by evidence in Cohen et al (2000) and in Keely and Quah s (1998) review of the empirical literature on R&D, technology and growth. The latter show that: (1) inputs in the knowledge production function are strongly related to knowledge output and (2) output of knowledge production is inaccurately proxied by patents, as Most knowledge accumulation does *not* occur from private firms R&D producing *patentable* knowledge. [8] A final observation is that spillovers do occur but do not happen automatically or completely. Hence, we do not assume *perfect* nor automatic knowledge spillovers, as is clear from the distinction between $\bar{f}$ and f_i in our specification and the fact that other firms knowledge enters (5) but not (4).

Cohen et al (2000) point out that secrecy and complementarities between the firm s existing activities and new activities are more important to secure the returns to innovation than patents. In the last decade, secrecy has become even more important relative to patents. Nevertheless patents are indispensable as a complementary appropriability mechanism and as a means to exchange knowledge. We interpret these survey results as follows. Firm-specific R&D creates knowledge with strong complementarities to the firm s own activities, both production and non-production activities. It can be easily kept secret and exclusively exploited by the firm itself since it is intimately linked to its own idiosyncrasies. When taking out or acquiring patents, knowledge of a wider applicability is involved. Patents ensure that the inventor gets a reward from any firm that applies this knowledge in production activities. However, the patent system cannot prevent, and in fact stimulates, the disclosure of information about general principles and ideas behind the invention that can be used in non-

[8] See Keely and Quah (1998), page 3, second italics added.

production activities.

We extend the regularities related to spillovers and knowledge accumulation -- familiar to the R&D-based endogenous growth literature -- to all non-production activities. To see the analogy between R&D and other non-production work, we may think of a new way of organising a firm. The implementation and development of new organisational schemes often takes years and builds on past experience. From the organisational scheme that a specific firm works out some more general principles can be useful for other firms too. If this information is written down or disseminates in some way, other firms might benefit too ($\bar{f}$). However, a next firm reorganising might use this information but still needs to go through the process of convincing, motivating and adapting to specific "own" circumstances[9] (that is increasing the firms specific knowledge stock, f_i). Though we argue the model to be applicable to the broad category of all non-production workers, the remainder of the analysis is expressed in R&D terms only.

3. The role of firm-specific R&D

To focus on the main mechanism driving the model results for the skill premium, we postpone the discussion of patentable knowledge to the next section. In this section we take the number of patents held by each firm as a given constant. All skilled labour is allocated to firm-specific R&D in equilibrium. Formally, this represents a special case of the model with $\chi = 0$.

3.1 Firm behaviour

Demand for unskilled and skilled workers is determined by the firms production and non-production decisions, given that firms are restricted by a downward-sloping demand curve for final output.

Skilled workers' output is not sold in the market directly.[10] By hiring skilled workers, the firm can invest in firm-specific knowledge. The wage the firm is willing to pay for skilled labour depends thus on the rate of return to investment in firm-specific knowledge. The firm

[9] Jovanovic (1997) argues that adjustment and implementation costs of ideas dominate the non-rivalness of knowledge.

[10] Clear examples are output of the marketing manager, the human resource manager, the product designers, and the organisational experts.

invests up to the point that the marginal return to investment in firm-specific knowledge equals the cost of capital. This no-arbitrage condition can be written as:[11]

$$\frac{p\left(1-\frac{1}{\varepsilon}\right)\frac{\partial x}{\partial f} + q\frac{\partial \dot{f}}{\partial f} + \dot{q}}{q} = r \ , \tag{7}$$

where ε is the elasticity of demand from equation (1) and q is the shadow value of firm-specific knowledge, or in other words the firms internal accounting price for non-production workers' output. The left-hand side of the equation represents the marginal return from non-production workers activities. The first term represents the value of their contribution to improving efficiency of production, the second term represents the value of their contribution to providing knowledge inputs for the process of investment in firm-specific knowledge, and the final term captures a capital gain (capturing the fact that if the price to knowledge accumulation increases over time, investing today in knowledge becomes more attractive).

The firm hires skilled labour up to the point where the marginal cost of hiring (the wage for skilled labour, w_H) equals its marginal product which is the marginal amount of knowledge it generates $\partial \dot{f}/\partial H_f$ valued at the price of knowledge q:

$$w_H = q\frac{\partial \dot{f}}{\partial H_f} \ . \tag{8}$$

Similarly, the firm hires unskilled labour up to the point where the marginal cost of hiring (the wage for unskilled labour, w_L) equals its marginal revenue product. Taking into account that the firm s demand curve for final goods slopes downward, we find:

$$w_L = p\left(1-\frac{1}{\varepsilon}\right)\frac{\partial x}{\partial L} \ . \tag{9}$$

[11]The following three equations can be straightforwardly derived from the firms dynamic optimization problem. Firms maximize profits, discounted by interest rate r, subject to (4),(5) and the downward sloping demand curve for its output. Suppressing the firm index i, we may write the Hamiltonian as $p(F(f,n,L))\cdot F(f,n,L) - w_L L - w_H H_f + qG(f,\bar{f},\bar{n},H_f)$, where $F()$ is the production function in (4) and $G()$ is the accumulation function in (5).

3.2 Short-run partial equilibrium

We now reduce the conditions governing firm behaviour to one equation. We assume that firms are symmetric. Because the mass of firms is one, in equilibrium the representative firm absorbs all labour ($L_i = L$ and $H_{fi} = H_f = H$). The symmetry assumption also implies that f and $\bar{f}$ grow at a common rate, denoted by g, which can be written (from (5)) as:

$$g \;=\; \xi f^{-(1-\alpha-\gamma)} H_f^{\lambda} \;. \tag{10}$$

Assuming that both H and L grow at a common rate l and evaluating the partial derivatives, we find:

$$\frac{w_L}{w_H}\frac{L}{H_f^{1-\lambda}}\frac{\lambda}{\delta}\beta\xi f^{\alpha+\gamma-1} \;+\; (\beta-\gamma)g \;+\; (\hat{w}_H-\hat{w}_L) \;+\; (\delta-\lambda)l \;=\; r-\hat{p} \;, \tag{11}$$

where hats denote growth rates. This equation equates the real cost of capital to the real return to investment. We can use it to study the partial-equilibrium short-run effects of an increase in the supply of high-skilled labour H by keeping the knowledge level f and the real cost of capital $r!p$ constant. Whenever the return to investment increases, there will be an induced demand for skilled labour and hence an upward pressure on their relative wage.

The first term on the lhs represents the *direct* effects of investment for production. If more skilled labour is employed the first term becomes smaller.[12] The reason is that the costs of productivity improvements, relative to production costs, rise with H because of diminishing returns ($\lambda < 1$). Through this channel, a higher supply of skilled labour reduces their relative wage. This is the *conventional effect* of an increase in skills.

The other terms on the lhs reflect the effects of knowledge growth on the future relative costs of (or return to) organizational change. Let us first consider the term $(\beta-\gamma)g$. On the one hand, the larger the impact of organizational change, as captured by g, on productivity of unskilled labour, as captured by β, the more attractive it is to invest. Large increases in productivity induce firms to invest now rather than later. To be able to undertake these

[12] If more *un*skilled labour is employed (L increases), the return to investment is higher, and hence the skill premium. This is due to the fact that more production workers benefit from the same increase in productivity due to the non-rivalness of knowledge. This is analogous to Acemoglu's (1998) mechanism. The mechanism driving our induced-investment effect relates to the second term on the lhs of equation (11).

investments, firms increase their demand for skilled labour. On the other hand, if knowledge spillovers from other firms are large, knowledge growth results in large reductions over time in the cost of organisational change, which reduces the incentive to invest now and makes firms willing to postpone investment, thus reducing the demand for skilled labour. If the scope for productivity improvements (β) is large and spillovers (γ) are small, firms are willing to invest more in response to a higher growth rate. Ceteris paribus, this increases demand for skilled labour. Employing more skilled labour increases the rate of productivity growth. Hence, if spillovers are small, this may increase the demand for skills. Thus the demand for skilled labour tends to increase because of this channel.

The third term on the lhs, the rate of increase in the skill premium, reflects the fact that if skilled labour becomes more expensive to hire over time, investment becomes more expensive over time, and it is attractive to undertake investment now rather than in future. This also increases the demand for skills, ceteris paribus.

3.3 General equilibrium

We now close the model by taking into account goods-market equilibrium and capital-market equilibrium. The former implies $C = x$, and $p_c = p$. The capital market is in equilibrium if the rate of return satisfies the Keynes-Ramsey rule (3), which can now be written as $r - \hat{p} = \vartheta + \rho\hat{x}$. Combining (3), (10) and (11), and using (4) to solve for $\hat{x}$, we find:

$$\left(\rho - (1 - \gamma/\beta) - \frac{L}{H_f}\frac{\lambda}{\delta}\frac{1}{w_H/w_L} \right) \beta g + \vartheta_l = \widehat{w_H/w_L} \ , \tag{12}$$

where $h_l \equiv \vartheta + [\lambda + \delta(\rho - 1)]l$. This equation in two unknowns, viz. the skill premium w_H/w_L and the growth rate g, subsumes equilibrium in the markets for output, unskilled labour and capital and will be shortly referred to as the no-arbitrage condition. By confronting it to the condition for equilibrium in the skilled labour market, eq. (10), we can determine the dynamics in general equilibrium.

Our main result is that an increase in the supply of skilled labour may increase the skill premium. We show this outcome for the assumption that there are constant returns with respect to knowledge accumulation in the non-production activities, that is $\alpha + \gamma = 1$. As a result, the rate of growth in the economy depends on the supply of skilled labour only; see (10). To avoid accelerating growth rates, we assume that there is no population growth ($l = 0$). Note that both restrictions are usual in endogenous growth literature.

The model is now fully represented by equation (10) and (12). Figure 1 depicts equation (10) as the vertical line labelled GG. The SS-curve in the figure is the locus for which the skill premium, w_H/w_L, is constant, as can be derived from equation (12). This curve slopes upward as no-arbitrage requires that a high rate of growth -- which makes it attractive to invest in knowledge by hiring skilled workers -- is met by high costs. Full employment of skilled labour requires that the economy is always on the GG line. The skill premium jumps immediately to its long-run value, given by the point of intersection between the GG line and the SS curve.

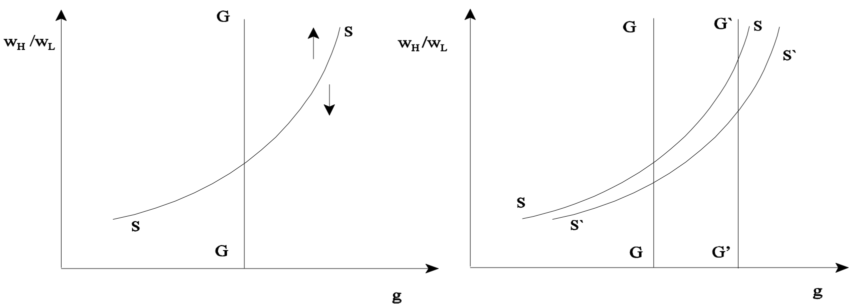

Figure 1. Firm-specific knowledge and the skill premium

An increase in the supply of skilled labour may raise wage inequality in general equilibrium, since, if H increases, the SS-locus shifts down and the GG-line shifts to the right. To find the conditions for a rising skill premium, we derive the closed-form solution for the skill premium. Substituting (10) into (12), and taking into account that $\alpha+\gamma=1$ and that the skill premium is constant, we find:

$$w_H/w_L = \frac{(\lambda/\delta)L}{(\vartheta/\beta\xi)H_f^{1-\lambda} + [\rho-(1-\gamma/\beta)]H_f} . \tag{13}$$

Differentiation with respect to H_f reveals that the condition for a rise in the skill premium is given by:

$$\alpha > \rho + (1-\beta)\frac{\gamma}{\beta} + (1-\lambda)\frac{\vartheta}{\beta g} . \tag{14}$$

This last condition neatly reveals four determinants that may cause the demand curve for skills to slope upward.

First, appropriability of the (intertemporal) returns to non-production activities (as measured by α) should be high. The mirror image of this is that spillovers to other firms (as measured by γ) should be low. This underlines our key assumption that skilled workers create the knowledge that is subsequently used as an essential input in non-production activities. If new knowledge only affects the firm's production activities and all knowledge inputs in non-production activities come from outside (i.e. $\alpha=0$), condition (14) is never satisfied and the demand curve for skills slopes conventionally downward. Note that most of the endogenous growth literature consider this case by assuming that all intertemporal spillovers from research are external effects for the individual firm.

Second, the cost of capital should not rise too fast with increased investment, that is, ρ should be small (note from the Keynes-Ramsey rule (3) that ρ governs the sensitivity of interest rates with respect to growth and investment). This emphasises that non-production labour is engaged in the *investment* process, rather than the production process. If firms hire more skilled labour, investment and growth rises in the economy, forcing households to save more. This induces them to require a higher rate of return on their savings, especially when they prefer a smooth consumption pattern (ρ large). When firms face a higher cost of capital, investments in firm-specific knowledge by hiring more skilled labour, becomes less attractive. The rise in the cost of capital thus mitigates the demand for skilled labour and partially offsets the rise in the skill premium.

Third, diminishing returns with respect to knowledge in production (as measured by $1-\beta$) reduce the skill premium. Diminishing returns reduce the value of additions to the knowledge stock, which are generated by hiring more skilled labour.[13]

Fourth, diminishing returns with respect to skilled labour in non-production activities (as measured by $1-\lambda$) reduce the skill premium. Diminishing returns reduce the marginal value of skilled labour for the firm and thus depress their wage.

[13]This effect vanishes if there are no spillovers (i.e. if $\gamma=0$). In this case, all knowledge is created inside the firm with constant returns with respect to knowledge (see (5) and note that $\alpha=1-\gamma=1$). On the firm level a constant rate of growth of knowledge can be attained equal to ξH_f^{λ} which translates in a constant rate of total factor productivity growth equal to $\beta\xi H_f^{\lambda}$. Hence, diminishing returns are no longer important. In contrast, if the firm relies on outside knowledge ($\gamma>0$), it takes into account that an increase in firm-specific investment *reduces* its rate of knowledge growth for a given rate of growth in the outside knowledge stock, $\bar{f}$. This hurts the firm more, the more important the diminishing returns in the use of knowledge in production are (as measured by $1-\beta$).

To summarize, a rise of the skill premium as a response to a higher supply of skilled labour requires that the intertemporal returns from an expansion of non-production activities accrue mainly to the firm rather than to shareholders (in the form of higher rates of return) or other firms (because of spillovers). Moreover, the returns should not fall too quickly because of diminishing returns in production or non-production activities. Only under these circumstances, the firm passes through the intertemporal returns to non-production workers in the form of higher wages for skilled labour.

While condition (13) was derived for the case of endogenous growth ($1-\alpha-\gamma = l = 0$), it turns out that under the same condition the skill premium rises in the short run if $1-\alpha-\gamma$, $l > 0$ (see appendix). In this case of semi-endogenous growth (Jones 1995), in the short-run growth changes as in an endogenous growth model, but the long-run growth rate is exogenous because the productivity of investment falls as more knowledge per worker is accumulated. The long-run effect on the skill premium vanishes together with the long-run growth effect. This again reveals that the upward pressure on the skill premium is crucially linked to increased investment opportunities, which make hiring skilled workers that produce investment goods (knowledge) more attractive.

4. Endogenous appropriability and patents

The model discussed in the previous section can explain the upsurge in inequality in the 1980s provided that the intertemporal returns can be appropriated sufficiently. To be able to explain *both* the decrease and the increase in inequality in the 1970s and 1980s respectively, the degree of appropriability should have altered over time. This section shows that appropriability changes endogenously in the model once we no longer fix the patent stock and no longer limit innovation to inhouse R&D. An increase in skilled labour supply causes a labour reallocation from patent development to firm-specific R&D. Since intertemporal knowledge spillovers can be appropriated in the latter research sector, but not in the former one, economy-wide appropriability improves. This mechanism simultaneously explains the skill premium time pattern and the downward trend in patent productivity.

4.1 Appropriability and endogenous growth

To analyse the full model that was outlined in section 2, we have to complete the equations describing households and producer behaviour, (1)-(9), with the behavioural equations for the research firms.

Free entry of research firms implies that the price of a patent, p_n, equals the production cost:

$$p_n = \frac{w_H}{\chi \bar{n}^{\mu} \bar{f}^{\phi}} \quad . \tag{15}$$

The demand for patents follows from the no-arbitrage condition analogous to equation (7):[14]

$$\frac{p\left(1-\frac{1}{\varepsilon}\right)\frac{\partial x}{\partial n}+\dot{p}_n}{p_n}=r \quad . \tag{16}$$

Comparing equation (16) with (7) reveals the crucial difference between the two types of research: the private return to firm-specific research includes a term valuing the contribution of current research to future research productivity ($q\partial\dot{f}/\partial f$), while the private return to developing patents does not include such an intertemporal return.

Equilibrium on the market for skilled labour now reads:

$$H_f + H_n = H \ . \tag{17}$$

The remainder of this section discusses symmetric steady-state equilibria with endogenous growth. The endogenous-growth requirement implies the following parameter restrictions: $\gamma = 1-\alpha-\nu$ and $\phi = 1-\mu$. To simplify expressions we set $\lambda = \delta = 1$. We introduce a variable for the ratio of the stock of firm-specific knowledge to the number of patents $A \equiv f/n$. This ratio is an indication of the degree of appropriability in the economy s research-capital stock. In the steady state, the ratio is constant and we denote the common balanced growth rate of f and n by g. Using (17), we can rewrite (5) and (6) as $\hat{f} = \xi A^{-\nu} H_f$ and $\hat{n} = \chi A^{\phi}(H - H_f)$, and equate the

[14] Cf. Footnote 11. The Hamiltonian for the producer's maximization problem now reads $p(F(f,n,L)) \cdot F(f,n,L) - w_L L - w_H H_f + qG(f,\bar{f},\bar{n},H_f) + (q_n - p_n)I_n$, where the final term captures patents: q_n is the costate variable associated to the patent stock and $I_n = \dot{n}$ is the firm's purchase of patents. Equation (16) follows from the optimality conditions with respect to I_n and n.

expressions to find the following expression for the balanced growth rate:

$$g = \frac{\chi A^{\phi} H}{1 + (\chi/\xi)\, A^{\nu+\phi}} \ . \tag{18}$$

Equation (18) is depicted in the upper panel of Figure 2 as the balanced growth (BG)-curve. The BG-curve is hump-shaped, reaching its maximum at $A^{\nu+\phi} = \phi/\nu$. At a low degree of appropriability (A), the economy has a relative abundance of patents which implies a low productivity of the patent sector. Balanced growth, however, requires both the stock of patents and the stock of firm-specific capital to grow at equal rates. This implies that skilled labour must be largely employed in the low-productive patent sector. Hence growth is low. Increases in A make the patent sector more productive and hence less resource consuming for balanced growth. This allows for a higher growth rate. Increasing A further reduces the research productivity within firms, making the accumulation of firm-specific capital the bottleneck (and lowering the feasible balanced growth rate again).

In equilibrium the return to patent development equals the cost of capital. We find this no-arbitrage condition by substituting (4), (9), and (15) into (16). Along a balanced growth path (where w_H/w_L and A are constant) this boils down to:

$$r - \hat{p} = \frac{L}{w_H/w_L}(1-\beta)\chi A^{\phi} \ . \tag{19}$$

The return to patent development is increasing in the patent elasticity in production $(1-\beta)$ and the production size (L), and is decreasing in the effective cost of research ($w_H/\chi A^{\phi}$).

A similar no-arbitrage equation holds for investment in firm-specific knowledge. The marginal return to inhouse R&D equals cost of capital, as in (11), which can be written along the balanced endogenous growth path as:

$$r - \hat{p} = \frac{L}{w_H/w_L}\beta\xi A^{-\nu} + \alpha g \ . \tag{20}$$

The structure is analogous to (19) again but for the term that indicates the dynamic externality that is appropriated (the strength of this mechanism is governed by α).

The cost of capital follows from the Ramsey rule, (3), and $\hat{x}=g$ from (4):

$$r-\hat{p} \;=\; \vartheta+\rho g \;. \tag{21}$$

Combining the capital-market equations, (16)-(21), we find the following relationship between growth and appropriability:

$$g \;=\; \frac{(1-\beta)\chi A^{\nu+\phi} \;-\; \beta\xi}{(\alpha-\rho)(1-\beta)\chi A^{\nu+\phi} \;+\; \rho\beta\xi}\vartheta \;. \tag{22}$$

The upper-panel of Figure 3 depicts equation (22) as the ARB-curve. Its upward slope implies that a higher growth rate is to be met with greater scarceness of patents to prevent arbitrage opportunities. High growth implies high returns to in-house R&D (see equation (20)). To equalise returns A has to increase, as is obvious from equation (19).

Combining the capital market equations (16)-(21), we can also derive the following relationship between the skill premium and the degree of appropriability in the economy s research-capital stock:

$$\frac{w_H}{w_L} \;=\; \left[(\alpha-\rho)(1-\beta)\chi A^{\nu+\phi} \;+\; \rho\beta\xi\right]\frac{L}{\alpha\vartheta A^{\nu}}. \tag{23}$$

The skill premium is unambiguously negatively related to appropriability A if $\alpha<\rho$. However, we from now on focus on the case where $\alpha>\rho$.[15] Then, the skill premium depends negatively on A at low levels of A and positively at high levels of A. Equation (23) is depicted as the U-shaped SS-curve in the lower panel of Figure 2.

[15] It can be easily checked that in the case where $\alpha<\rho$, the skill premium conventionally decreases with the supply of skilled labour. Note that also in the previous section we found that $\alpha>\rho$ is a necessary condition for the conventional effect not to dominate, see (14).

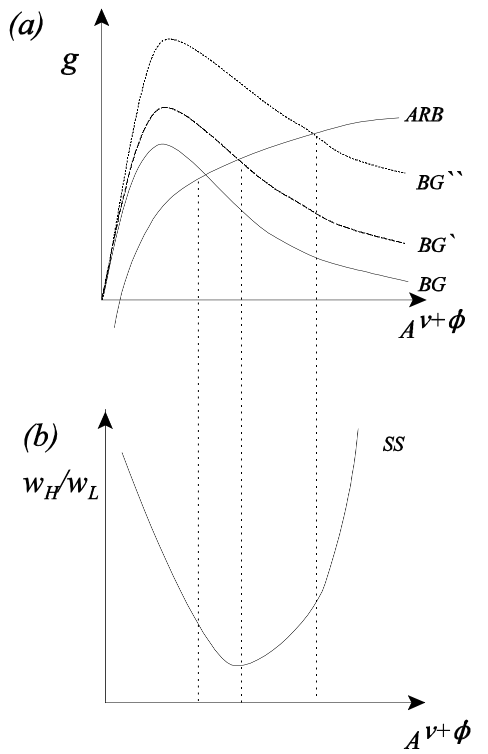

Figure 2 General equilibrium with endogenous appropriability

Now we can again analyse the effects of an increase in the supply of skilled labour. The BG-curve shifts upward to BG . The intersection of the BG - and ARB-curve determines the new equilibrium in which the degree of appropriability of the research-capital stock is higher. In the lower panel, the skill premium decreases. Shifting the BG -curve up by further increasing the supply of skill learns that the degree of appropriability increases further, but now the skill premium increases. The movement along the SS curve is thus consistent with the empirics of the skill premium time pattern in the 1970s-1980s. There is also evidence on the rise in the appropriability indicator. Cohen et al (2000) document a rise in the importance of secrecy and complementary firm-specific activities in protecting the returns to innovation, relative to the importance of patents.

Why does the skill premium fall when skilled labour is scarce but rise in a skilled-labour-abundant economy? More skilled labour implies higher growth and larger benefits to internalizing intertemporal spillovers from R&D. The faster growth, the more skilled labour is employed in firm-specific research departments, since firms can appropriate the intertemporal benefits of high growth rates. Higher growth rates increase the demand for skilled labour, thus counteracting the conventional downward pressure on skill premiums. Indeed, equations (19) and (20) point out that higher growth benefits firm-specific R&D, see equation (20). Arbitrage shifts the economy towards relatively more firm-specific knowledge: equality of the returns in (19) and (20) requires a rise in A. This shift reduces the returns from increasing the firm's labour productivity (see the first term on rhs of (20)), and the return to firm-specific R&D relies relatively more on the appropriated intertemporal spillovers (see the second term on the rhs of (20)). On the economy-wide level, appropriability of dynamic gains becomes more important when growth increases. Hence, while for low supply of skilled labour and correspondingly low growth rates the conventional effect dominates, for high supply and high growth, the appropriability effect dominates, which increases skill premiums.

4.2 The patent-productivity puzzle

Empirical research documents a fall in productivity of R&D in terms of patent output per real dollar of R&D. The fall is found for both the 1970s and the 1980s, that is, a monotonic fall that contrast with the U-shaped pattern for the skill premium in the same period.[16]

Our extended model not only generates the observed pattern for the skill premium, but also predicts that it is accompanied by a fall in patent productivity. A gradual rise in the supply of high-skilled labour shifts research activity towards more firm-specific research. Typically, firm-specific research generates less visible research output: secrecy and tacitness of the knowledge generated in this way make that the propensity to patent is typically lower and innovation is underestimated in the innovation statistics. As a result, research *output* statistics tend to report a fall in output when research shifts to firm-specific research, because these statistics concentrate on patents. On the research *input* side, however, it is difficult to separate out the inputs in firm-specific research from those aimed at developing patents. Hence, typically, measured patent output falls, but measured input is not corrected for the reduction in inputs directed at patent development.

In the model, the following ratio comes closest to the statistic that is used in the empirical literature on research productivity:

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[16] The upsurge in patenting (even per R&D dollar) in the late eighties is, according to Kortum and Lerner (1998), associated with an increase in research productivity. The increase could be mimicked in the model by increasing the exogenous research productivity in the patent sector. This point is ignored further as it empirically still unclear how important the institutional changes from 1984 onward have been in affecting the patent practice (see Jaffe, 1999).

$$\frac{\dot{n}}{Hw_H/p_n} \tag{24}$$

that is, the number of new patents divided by the total real cost of R&D, ignoring the distinction between inputs into firm-specific research and those into other research. If inputs were measured correctly, the productivity statistic would be $\dot{n}p_n/H_nw_H$, which would be constant and equal to unity (in the steady state) due to our assumption of zero profits in the research sector, see (6) and (15). However, the ratio above has total inputs H instead of H_n in the denominator, and because of zero profits the ratio boils down to H_n/H which is directly related to the appropriability measure A in the steady state (combine (18) and $\dot{n}/n=g=\chi A^{\phi}$ from (6)):

$$\frac{\dot{n}}{Hw_H/p_n} = \left(\frac{\dot{n}p_n}{H_nw_H}\right)\frac{H_n}{H} = \frac{H_n}{H} = \frac{1}{1+(\chi/\xi)A^{\nu+\varphi}} \tag{25}$$

Hence, when H increases, A increases monotonically, and measured patent productivity falls monotonically. Thus from the 1970s to the late 1980s we register a fall in patent productivity.

5. Conclusion

Wage inequality increased in the 1980s in the majority of OECD countries. In the evaluation of the potential explanations for this phenomenon, trade, institutions, technology and relative factor supplies (education), the technology explanation was left by default.

We showed that an increased endowment of skilled labour might induce an increase in the relative wage for skilled labour. The argument that this paper developed starts with the explicit recognition that skilled labour or non-production workers perform tasks that are similar to investment activities, that is, skilled workers produce knowledge capital. Once it is recognised that skilled workers *use* knowledge *while producing* knowledge, increased availability of skilled workers increases their wages, provided that (1) the degree of appropriability of investment in organisational capital is sufficiently large, (2) the investment cost do no rise too fast and (3) diminishing returns related to knowledge accumulation do not set in too strongly.

In order to focus on the novel connection between appropriability and wage inequality, we deliberately left out some important aspects. First, as explained in the introduction, we did not consider within-group inequality. Second, we did not examine endogenous responses of labour supply to changes in equality. The literature already has developed useful insights in these aspects (see Galor and Moav (1998) and Acemoglu (1998, section 4) respectively). These insights can be easily applied to our model. Another important extension would be the distinction between major innovations and incremental technical change. It would allow to study more explicitly in our set-up the introduction and diffusion of the computer which plays a important role in the wage inequality debate. Moreover, since appropriability is likely to differ between incremental change and major inventions, the extension could directly interact with the central mechanism in our approach.

Appendix: non-scale growth

In this appendix we analyse the more general version of the model presented in section 3. We assume that there are diminishing, rather than constant, returns with respect to knowledge in non-production activities, and we take into account population growth ($\alpha+\gamma<1$, $l>0$). The main difference with the case in the previous section is that now long-run growth becomes independent of the size of the skilled labour force. Hence, there is no scale-effect on the growth rate from an increase in the supply of skills.

The growth rate depends on the supply of skilled labour and on the stock of firms-specific knowledge accumulated in the past, see equation (10). Accordingly, the growth rate is a predetermined variable that changes over time. Differentiating (10) with respect to time yields the equation of motion for the growth rate:

$$\hat{g} = \lambda l - (1-\alpha-\gamma)g \ . \tag{A.1}$$

Hence the GG locus for constant growth rate reads

$$g = \lambda l \ / \ (1-\alpha-\gamma) \ . \tag{A.2}$$

The SS-locus is the same as in the case of endogenous growth (except for the fact that ϑ_1 takes a different value because of population growth) and follows directly from (12). Figure 3 depicts the phase diagram that results from equations (12) and (A.1). Transitional dynamics occur along the upward-sloping saddle path.

To analyse the consequences of an increase in the supply of skilled labour, we now need to distinguish between long-run and short-run effects. For simplicity, we consider a permanent increase in H at $t=0$, but allow H to grow at rate l at all other dates.

The long-run growth rate is not affected by the supply shock (GG-locus remains unchanged), while the SS-curve shifts down. Hence in the long run, the skill premium unambiguously declines in response to an increased supply of skilled labour. In the short run, the growth rate increases by the expansion of non-production jobs. The combination of the shift of the SS locus and the short-run increase of the growth rate produces a (short-run) result that is very similar to that in the endogenous growth case analysed in the main text. Indeed, the skill premium may increase in the short run. To derive an exact condition for the upward-sloping demand curve to arise, we linearize equations (12) and (A.1) around the steady state and calculate the short-run response of the skill premium to a change in the supply of skilled labour. The linearized system reads:

$$\begin{bmatrix} \dot{\widetilde{w_H/w_L}} \\ \dot{\tilde{g}} \end{bmatrix} = \begin{bmatrix} a+\vartheta_l & -\vartheta_l \\ 0 & -\lambda l \end{bmatrix} \begin{bmatrix} \widetilde{w_H/w_L} \\ \tilde{g} \end{bmatrix} + \begin{bmatrix} a+\vartheta_l \\ 0 \end{bmatrix} \tilde{H}_f \ , \tag{A.3}$$

where tildes refer to percentage deviations from the initial steady state (log-linearized variables) and $a/\beta g[\rho-(1-\gamma/\beta)]$. From (10) we find the initial change (a time t=0) in the growth rate (which is predetermined):

$$\tilde{g}(0) = \lambda \tilde{H}_f \ , \tag{A.4}$$

where $\tilde{H}_f$ is the permanent shock to the skill endowment.
The stable root of this system is λl. Hence, we can calculate the jump in the skill premium as:

$$\widetilde{w_H/w_L}(0) = -\left(\frac{\lambda l + a + (1-\lambda)\vartheta_l}{\lambda l + a + \vartheta_l} \right) \tilde{H}_f \ . \tag{A.5}$$

The skill premium increases in the short run if the expression in parenthesis is negative. Taking into account the definition of a given above, we find the following condition:

$$\alpha > \rho + (1-\beta)\frac{\gamma}{\beta} + (1-\lambda)\frac{\vartheta_l}{\beta g} \ . \tag{A.6}$$

Note that this is exactly the same condition as for the endogenous growth case, see (14), although now of course α and γ no longer sum up to unity (and ϑ takes a different value because of population growth). Hence, the very same mechanisms as already explained in the main text apply. The intuition behind this similarity is also provided in the main text.

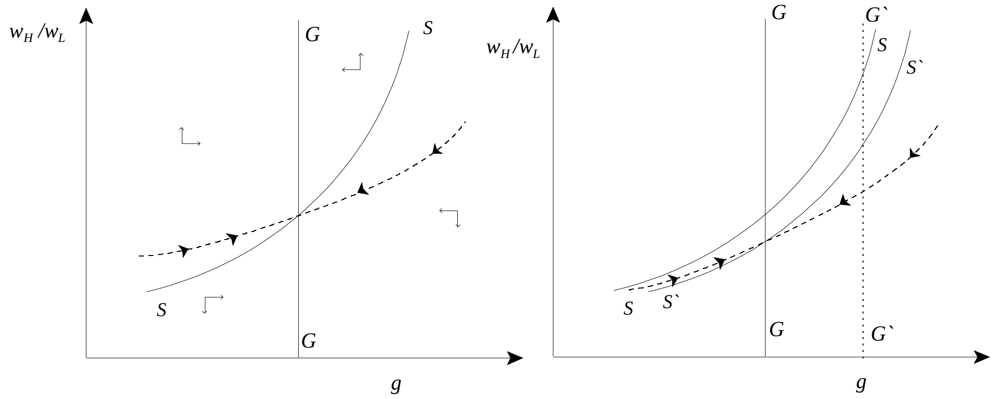

Figure 3. The skill premium with firm-specific and semi-endogenous growth

References.

Acemoglu, D. (1998) Why Do New Technologies Complement Skills? Directed Technical Change and Wage Inequality, *Quarterly Journal of Economics*, Vol. 113, No. 4, 1055-89.

Aghion, P. and P. Howitt (1998) *Endogenous Growth Theory*, The MIT Press, Cambridge, Massachusetts, London.

Autor, D.H., L.F. Katz and A.B. Krueger (1998) Computing Inequality: Have Computers Changed the Labour Market?, *Quarterly Journal of Economics*, Vol. 113, 1169-1213.

Bartel, A.P. and F.R. Lichtenberg (1987) The Comparative Advantage of Educated Workers in Implementing New Technology, *Review of Economics and Statistics*, Vol. LXIX, No. 1, 1-11.

Berman, E., J. Bound and Z. Griliches (1994) Changes in the Demand for Skilled Labor within U.S. Manufacturing: Evidence from the Annual Survey of Manufactures, *Quarterly Journal of Economics*, Vol. 109, 367-397.

Bound, J. and G. Johnson (1992) Changes in the Structure of Wages in the 1980's: An Evaluation of Alternative Explanations, *American Economic Review*, Vol. 82, No. 3, 371-392.

Caselli, F. (1999) Technological Revolutions, *American Economic Review*, Vol. 89, 78-102.

Cohen, W. M.., R. R. Nelson, and J. P. Walsh (2000) Protecting Their Intellectual Assets: Appropriability Conditions and Why U.S. Manufacturing Firms Patent (or Not), NBER Working Paper 7552

DiNardo, J.E. and J.S. Pischke (1997) The Returns to Computer Use Revisited: Have Pencils Changed the Wage Structure Too?, *Quarterly Journal of Economics*, Vol. 112, 291-303.

Dixit, A.K. and J.E. Stiglitz (1977), Monopolistic Competition and Optimum Product Diversity, *American Economic Review*, Vol. 67, 297-308.

Dosi, G. (1988) Sources, procedures and microeconomic effects of innovation, *Journal of Economic Literature*, 26, pp. 1120-1171.

Galor, O. and D. Tsiddon (1997) Technological Progress, Mobility, and Economic Growth, *American Economic Review* 87 (June), 363-382.

Galor, O. and O. Moav (1998) Ability Biased Technological Transition, Wage Inequality and Growth, CEPR Discussion Paper No. 1972. Forthcoming in Quarterly Journal of Economics.

Greenwood, J. and M. Yorukoglu, (1997) "1974," *Carnegie-Rochester Conference Series on Public Policy*, Vol. 46, 49-95.

Grossman, G.M., and E. Helpman (1991) *Innovation and Growth in the Global Economy*, Cambridge, MA: MIT Press.

Jaffe, A.B., M. Trajtenberg and R. Henderson (1993) "Geographic Localisation of Knowledge Spillovers as Evidenced in Patent Citations," *Quarterly Journal of Economics*, Vol. 103, No. 3, 577-598.

Jaffe, A.B. (1999) "The U.S. Patent System in Transition: Policy Innovation and the Innovation Process," NBER Working Paper No. 7280.

Jones, C.I. (1995) "R&D based Models of Economic Growth," *Journal of Political Economy* 103, 759-784.

Jovanovic, B. (1997) "Learning and Growth," in D. Kreps and K. Wallis (eds.) *Advances in Economics and Econometrics: theory and applications, seventh world congress* Vol. II, Cambridge University Press Ch. 9.

Katz, L.F. and K.M. Murphy (1992) "Changes in relative wages, 1963-1987: Supply and demand factors," *Quarterly Journal of Economics*, Vol.107, No.1, 35-78.

Keely, L.C. and D. Quah (1998) "Technology in Growth," CEPR Discussion Paper No. 1901.

Kiley, M.T., (1999)"The Supply of Skilled Labour and Skill-Biased Technological Progress," *Economic Journal*, Vol.109, No.458, p.708.

Kortum, S. (1993) “Equilibrium R&D and the Patent-R&D Ratio: U.S. Evidence,” *American Economic Review*, Vol. 83, 450-57.

Kortum, S. and J. Lerner (1998) “Stronger Protection or Technological Revolution: What Is behind the Recent Surge in Patenting?” *Carnegie Rochester Conference Series on Public Policy*, Vol. 48, 247-304.

Krueger, A.B. (1993) “How Computers Have Changed the Wage Structure: Evidence from Micro Data, 1984-1989,” *Quarterly Journal of Economics*, Vol. 99, 99-118.

Lloyd-Ellis, H (1999) “Endogenous Technological Change and Wage Inequality,”*American Economic Review*, Vol. 89, 47-77.

Machin, S. and J. van Reenen (1998) “Technology and Changes in Skill Structure: Evidence From Seven OECD Countries,” *Quarterly Journal of Economics*, Vol. 113, No. 4, 1215-1244.

OECD (1993) *Employment Outlook 1993*, Paris

Peretto, P. (1998) “Technological Change and Population Growth,” *Journal of Economic Growth*; Vol. 3, No. 4, 283-311.

Peretto, P. (1999) “Cost Reduction, Entry, and the Interdependence of Market Structure and Economic Growth,” *Journal of Monetary Economics* 43, 173-195.

Romer, P.M. (1990) “Endogenous Technological Change,” *Journal of Political Economy*, 98, s71-s102.

Smulders, J. and Th. van de Klundert (1995) “Imperfect Competition, Concentration and Growth with Firm-specific R&D,” *European Economic Review* 39, pp. 139-160.

Thompson, P and D. Waldo, (1994) “Growth and Trustified Capitalism,” *Journal of Monetary Economics*, No. 34, Vol. 3, 445-62.